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MASTER THESIS WORK

**Binary coherent beam combining with
semiconductor tapered amplifiers at
795 nm**

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Binary coherent beam combining with semiconductor tapered amplifiers at 795 nm

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Abstract. We present a coherent-beam-combining (CBC) experiment using a 795 nm diode laser as a technique to achieve more power by combining two beams. Two Gaussian beams are made to interfere while controlling polarization, amplitude and their relative phase, in a modified Mach-Zehnder interferometer coupled with a polarization interferometer. The output power is locked using a split detector, thus stabilizing its performance and the final output. Next, we explore the polarization-beam-combining (PBC) in this new setup, yielding an efficiency of 80.9% for CBC – polarized light– and 91.7% for PBC – non-polarized light–. We ran a tapered amplifier (TA), controlling its current, temperature and heat dissipation, whose mechanical housing is currently in the optimization phase. In the sequel we shall be installing a TA on each arm of the Mach-Zehnder interferometer to obtain a brighter source. One interesting application of this work is its use in atomic-physics experiments (using rubidium) and second order interactions in crystals.

PACS numbers: 42.25.Hz (interference), 42.25.Kb (coherence), 42.25.Ja (polarization), 42.55.Px (semiconductor lasers) 42.60.Jf (beam characteristics)

Keywords: coherent beam combining, polarization beam combining, semiconductor laser, tapered amplifier, Mach-Zehnder.

1. Introduction

Semiconductor lasers are limited by heat dissipation and facet damage, while, on the other side, high power lasers and high beam quality have a strong impact in laser research and industry. A viable solution for such semiconductor units is high-efficiency beam combining, for power scaling, while maintaining good beam quality.

This report is structured as follows: First, we define the terms *beam combining* and *coherent beam combining* (CBC), *Gaussian beams*, and *tapered amplifier*. Next, we describe the *interference of two Gaussian beams* followed by the experimental setup. We also describe the experimental arrangement for an *optical power amplifier* using a tapered amplifier. Lastly, after drawing the main conclusions, there is a detailed discussion concerning our future research.

The main contributions of this work are performing a CBC experiment with a 795 nm diode laser with a new technique to lock the power and to articulate the details of two interfering beams to obtain CBC. Almost all previous efforts in CBC are summarized in the paper by Fan T. Y. 2005 [1].

1.1. Beam combining

Beam combining is one of the different techniques explored to obtain the power scaling of laser sources with high beam quality. It consists in combining the output of several laser sources in order to obtain a single output beam. This has been a long-standing problem in laser technology because the goal is not only to add the power of many lasers, but also to preserve the beam quality. It is not enough to combine the beams *side-by-side*, increasing the beam area while not decreasing the beam divergence, reducing thus the beam quality. There are nowadays three different approaches in beam combining with high beam quality:

- **Coherent beam combining** (CBC) which combines different mutually coherent sources of the same wavelength.
- **Spectral beam combining** (SBC), also called wavelength beam combining, wherein the devices operate at different wavelengths.
- **Polarization beam combining** (PBC) which combines two orthogonally polarized beams in a polarizer. This method is not scalable because the output is non-polarized light, not being possible to combine more than two beams.

The method of coherent beam combining requires mutual temporal coherence rather than the spectral beam combining, but SBC generates an output with several spectral components. SBC is more graceful degradation, because the failure of one emitter reduces the output power but the CBC technique affects the beam quality. Despite the advantages of spectral beam combining [1, 2], we use coherent beam combining because we are interested in a narrow-bandwidth source that is achieved by this technique.

In CBC the phase and polarization of the fields must be controlled so that there is constructive interference. In active feedback implementations, path-length differences among array elements are detected, and then feedback is used to equalize the optical path lengths modulo 2π .

1.2. Gaussian beam

The most prominent solution of the paraxial Helmholtz equation is the so-called **Gaussian beam** [3]. Most lasers emit beams with a Gaussian profile:

$$\tilde{U}(\mathbf{r}) = \frac{\tilde{U}_o}{q(z)} \exp\left(-ik \frac{x^2 + y^2}{2q(z)}\right) e^{ikz}, \quad q(z) = z - iz_0. \quad (1)$$

We can rewrite (1) to separate the amplitude from the phase of this envelope. Given the beam parameter $\frac{1}{q(z)}$:

$$\frac{1}{q(z)} = \frac{1}{z - iz_0} = \frac{1}{R} + i \frac{\lambda}{\pi w^2}, \quad (2)$$

(1) takes the form

$$U(x, y, z) = \frac{U_0 w_0}{z_0 w(z)} e^{-\frac{x^2+y^2}{w^2}} e^{ikz + ik \frac{x^2+y^2}{2R} - i\xi}, \quad (3)$$

where

$$\left\{ \begin{array}{l} R = z \left[1 + \left(\frac{z_0}{z} \right)^2 \right], \quad w = \sqrt{\frac{\lambda z_0}{\pi}} \sqrt{1 + \left(\frac{z}{z_0} \right)^2} \\ w_0 = w(0) = \sqrt{\frac{\lambda z_0}{\pi}}, \quad \xi(z, z_0) = \arctan \left(\frac{z}{z_0} \right) \end{array} \right\} \quad (4)$$

(3) is known as the *complex amplitude* of the Gaussian beam while (4) gives the parameters of the beam.

1.3. Tapered amplifier

A tapered amplifier (TA) [8, 9], which costs nearly 2000 euros, is a semiconductor chip (approximately $2 \text{ mm} \times 2 \text{ mm} \times 6 \text{ mm}$) that exhibits broadband fluorescence and can amplify an input light beam (i.e. from $\sim 20 \text{ mW}$ to $\sim 500 \text{ mW}$). Moreover, a narrowband input yields a narrowband output, being fed by $\sim 1.5 \text{ A}$ to $\sim 5 \text{ A}$ (depending on the model) of a very stable source (laser current driver). Both the broadband emission and the amplification of the light can be temperature-tuned by using a controller. Tapered amplifiers are used as optical power amplifiers [5] and in external cavity setups [8].

2. Theory and experimental setup

2.1. Coherent beam combining: interference of two Gaussian beams

Consider two Gaussian beams incident on the XY plane. We can assume, without loss of generality, that the first beam is centered; while the second beam is tilted, making an angle β with the Z -axis and is displaced from the center (on the XY plane) a distance ϵ in the X -axis. Therefore – see section 1.2 – we can describe the electric field $U(x, y)$ (see (3)) or $E(x, y)$ of the first beam as follows:

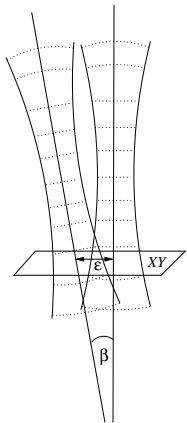
$$U_1(x, y, z) = U_{10} e^{-\frac{x^2+y^2}{w_1^2}} e^{ik(z + \frac{x^2+y^2}{2R}) - i\xi + i\delta_1}, \quad (5)$$

and of the second as [4]:

$$U_2(x, y, z) = U_{20} e^{-\frac{(x-\epsilon)^2 + (\cos^2 \beta)y^2}{w_2^2(z)}} e^{ik(z \cos \beta - y \sin \beta + \frac{x^2 + \cos^2 \beta y^2}{2R}) - i\xi + i\delta_2}, \quad (6)$$

where U_{10} and U_{20} are the amplitudes of the beams at a fixed z . The interference pattern produced on the detection plane is given by

$$I(x, y) = |U_1|^2 + |U_2|^2 + U_1 U_2^* + U_1^* U_2. \quad (7)$$



Interference of two Gaussian beams

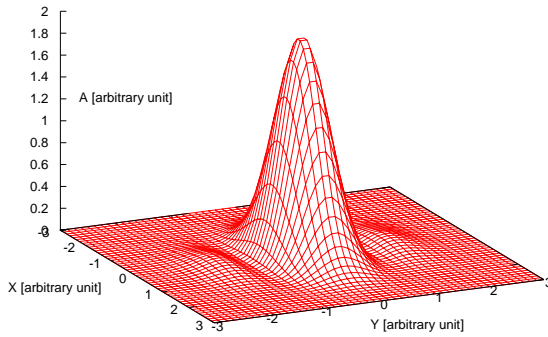
Performing the calculations and assuming that z is fixed we obtain

$$\begin{aligned}
 I_{11} &= |U_{10}|^2 e^{-\frac{2(x^2+y^2)}{w_1^2}}, \\
 I_{22} &= |U_{20}|^2 e^{-\frac{2((x-\epsilon)^2+\cos^2\beta y^2)}{w_2^2}}, \\
 I_{12^{*+1*2}} &= U_{10}U_{20}e^{-\left(\frac{(x^2+y^2)}{w_1^2}+\frac{(x-\epsilon)^2+\cos^2\beta y^2}{w_2^2}\right)} \times \\
 &\quad \times 2 \cos\left(k(y \sin(\beta) - z \cos(\beta) + z + \frac{y^2 \sin^2 \beta}{2R}) + \delta_1 - \delta_2\right).
 \end{aligned}$$

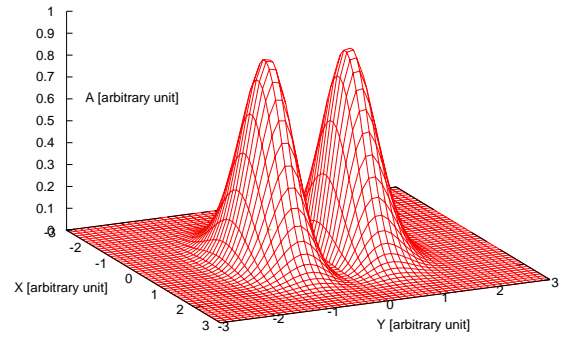
The last equation is exact in the *Gaussian beam theory*, which we can plot (integrate) to obtain the interference pattern (power). Nevertheless, we can obtain some insight –intuition– using the following approximations.

The interference term carries the behavior of the fringes, that are located in the Y -axis. Assuming that we have only one fringe we can estimate β as follows: $ky \sin \beta \approx 2\pi \rightarrow \beta \approx \arcsin \frac{\lambda}{y}$. We define $\delta_1 - \delta_2 = \delta$ and approximate $\sin \beta \approx \beta$ and $\cos \beta \approx 1$. With all these assumptions and ignoring terms of fourth order, [‡] we obtain the following equation, see figure 1.

$$I(x, y) = I_{11} + I_{22} + 2\sqrt{I_{11}}\sqrt{I_{22}} \times \cos(ky\beta + \delta) \quad (8)$$



(a)



(b)

Figure 1. Qualitative behavior of the function $I(x, y)$ assuming $I_{11} = I_{22}$ and $\beta \neq 0$. (a) Constructive interference $\delta = 2n\pi$, $n \in \mathbb{Z}$ (b) Destructive interference $\delta = (2n+1)\pi$, $n \in \mathbb{Z}$

In the present case we are interested in the total power and in the difference between the upper and lower beams. Therefore the signals are proportional to

$$P_{total} = \int_Y \int_X I(x, y) dx dy, \quad (9)$$

[‡] $y\beta \gg \frac{y^2\beta^2}{2R}$ Because the minimum of R is $2z_0$ and $z_0 \approx 1$ m in the current setup.

$$P_Y = \int_X \left(\int_0^{y_0} I(x, y) dy - \int_{-y_0}^0 I(x, y) dy \right) dx, \quad (10)$$

and

$$P_X = \int_Y \left(\int_0^{x_0} I(x, y) dy - \int_{-x_0}^0 I(x, y) dx \right) dy. \quad (11)$$

After performing these calculations, we obtain the remarkable results (the explicit dependence of β and ϵ , and the phase dependence on P_{total} and P_Y)

$$P_{total} = \frac{\pi w^2}{2} \left(U_{10}^2 + \sec \beta U_{20}^2 + 2U_{10}U_{20}e^{\frac{-k^2 w^4 \beta^2 - 4\epsilon^2}{8w^2}} \cos \delta \right), \quad (12)$$

$$P_Y = f_Y(\epsilon, \beta, w, k, U_{10}, U_{20}) \sin(\delta), \quad (13)$$

$$P_X = f_{X1}(\epsilon, \beta, w, k, U_{10}, U_{20}) \cos(\delta) + f_{X2}(\epsilon, \beta, w, k, U_{10}, U_{20}), \quad (14)$$

where we have assumed $w_1 \approx w_2 \approx w$. The functions f_Y, f_{X1}, f_{X2} are written in terms of the error function $-\text{Erf}(z), z \in \mathbb{C}$, also called Gauss error function. Since the actual shape of these functions depends on alignment and other experimental factors, it is different for each setup.

2.1.1. Discussion. We can obtain some quantitative results, if we take $U_{10} = U_{20}$ and $\beta \ll 1$. The *interference visibility* is defined as

$$\text{Visibility} = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} = e^{\frac{-k^2 w^2 \beta^2}{8}} e^{-\frac{\epsilon^2}{2w^2}} \quad (15)$$

We note that to obtain a large visibility it is necessary to overlap the two beams as much as possible $\epsilon \rightarrow 0$, with equal amplitudes U_{10} and U_{20} , and a very small angle β . A value of $\beta = 0.1$ mrad leads to an efficiency of 92%, however, such a small angle requires using micrometric screws in some of the mirror mounts of the setup. In the case of a one-inch mirror D a screw with a thread χ of 1 μm is needed.

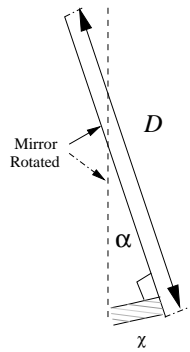
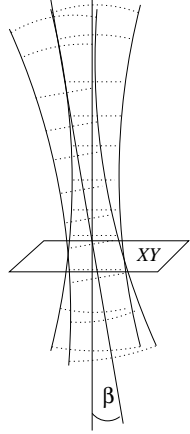
$$\chi = \tan(\alpha) \frac{D}{2} = \tan(0.1 \times 10^{-3}) \left(\frac{0.0254 \text{ m}}{2} \right) \approx 1 \mu\text{m} \quad (16)$$

2.2. Coherent beam combining: experiment

The experimental arrangement shown in figure 2 satisfies all conditions (see section 1.1) to successfully produce CBC.

2.2.1. Optics. A diode laser locked to the rubidium D1 line at 795 nm is fiber coupled to a **modified Mach-Zehnder interferometer** –a set of paddles is used to control roughly the input polarization–. This interferometer consists of two polarization beam splitters (PBS), two mirrors, one of which is moved using a piezoelectric transducer (PZT). PBS1 separates the horizontal and vertical polarizations (H and V modes) of the incident beam. The PZT controls the relative phase (modulo 2π) between these

If $\epsilon \rightarrow 0$
interference
becomes:



Mirror and
thread

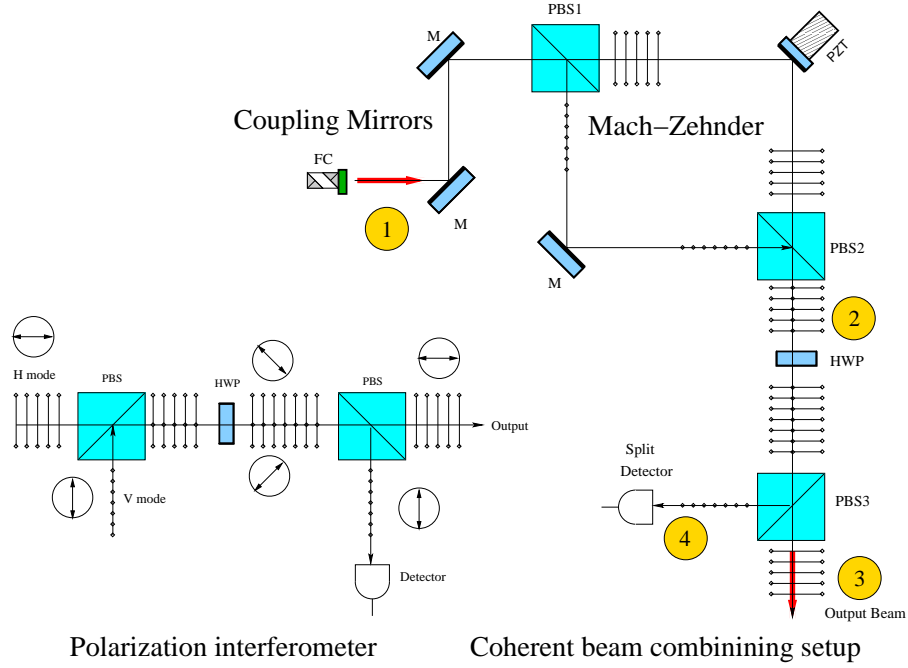


Figure 2. Coherent beam combining interferometer. (FC: fiber coupling, M: dielectric mirror, PBS: polarization beam splitter, PZT: piezoelectric transducer, HWP: half-wave plate).

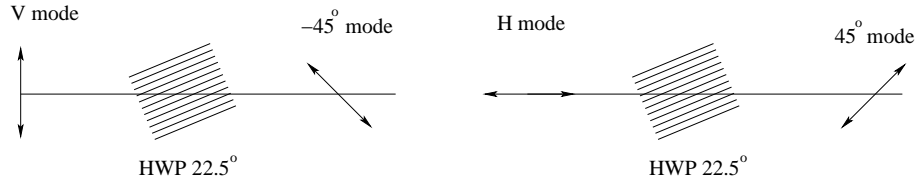


Figure 3. The role of the half-wave plate is to rotate the polarization in order to achieve the interference of the beams.

two beams and it is used to actively stabilize the output (see section 2.2.2). PBS2 is used to combine these two polarizations. Next, the beam enters a **polarization interferometer** that consists of two PBS and a half-wave plate (HWP) –The role of the HWP is illustrated in figure 3–. The polarization interferometer works as follows: Light coming out of PBS2 passes through the HWP, which decomposes each mode into two orthogonally polarized beams with a phase difference –depending on the rotation angle θ of the HWP–. PBS3 combines the beams and produces a wave pattern described in section 2.1. We can tilt and displace one beam using the mirrors – limited only by the resolution of the screws–. For the particular case of $\theta = 22.5^\circ$ on the HWP the H and V modes are converted into 45° and -45° modes, see [6]. Since each mode is a linear combination of H and V modes, they can interfere.

2.2.2. Stabilization and locking of output power. We used a new technique of **locking** and **active stabilizing** the power of the interferometer similar to that presented in [7].

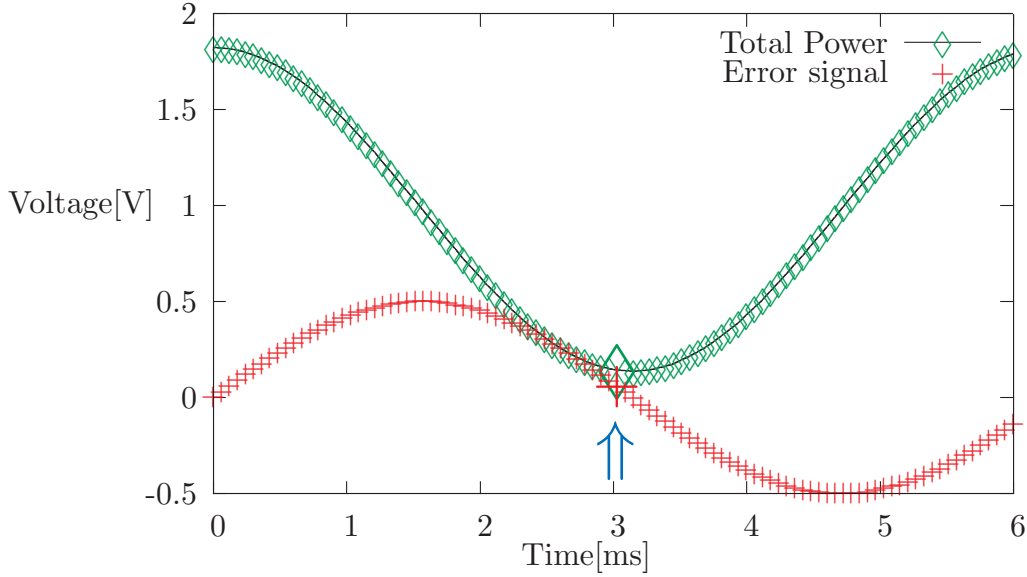


Figure 4. Oscilloscope trace. The signal \diamond is proportional to the total power P_{total} in the quadrant detector (④) and the signal $+$ is the error signal which is proportional to $P_Y - Y$ component on the quadrant detector-. We lock the system at the point \uparrow .

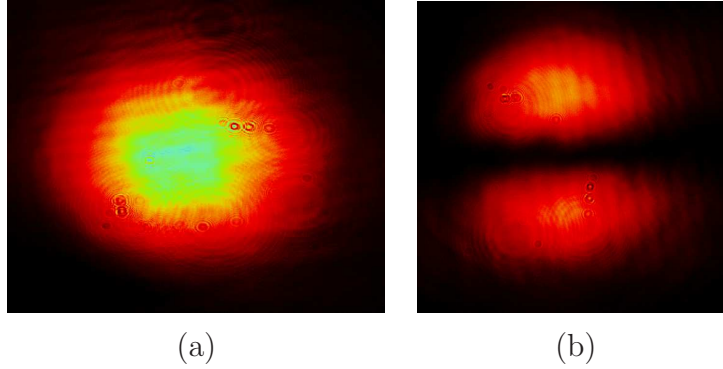


Figure 5. Images corresponding to figure 1, $\beta \approx 1.6 \pm 0.4$ mrad, $\epsilon \rightarrow 0$, $I_{11} \sim I_{22}$.

We adjusted the phase such that we obtain almost all the power in one output (figure 1 (a)), while the other output has the complementary interference pattern (figure 1 (b)).

To lock the power we inserted a quadrant detector in one output, which gives signals proportional to P_Y and P_{total} . Recalling the phase dependence in (12) and (13), we can use P_Y as an error signal in a feedback system and lock the power at the zero on the error signal to obtain the maximum power on the other output. In figure 4 we have a typical trace of the oscilloscope as an example.

2.2.3. Results Two images obtained with a CCD camera at points ③ (figure 5 (a)) and ④ (5 (b)) are shown in figure 5. Both we taken with the same alignment, (a) has an angle $\beta \approx 1.6$ mrad. We note that these pictures correspond to the qualitative behavior described in figure 1.

Figure 6 shows images taken at ③ for different angles β .

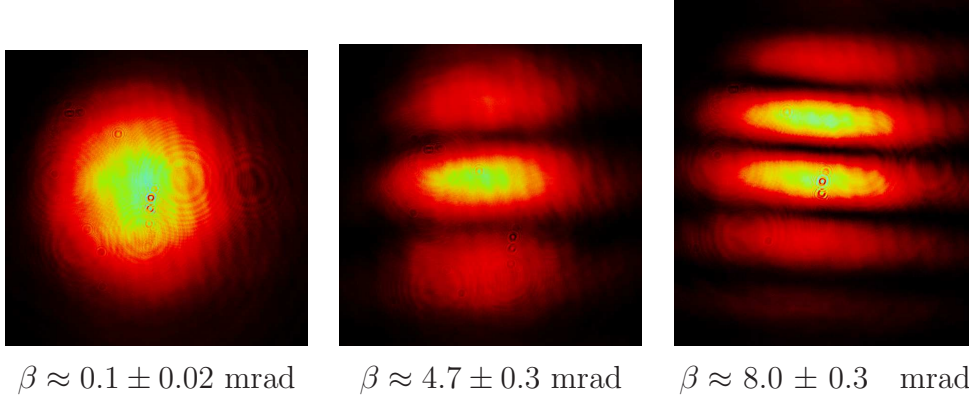
**Figure 6.** Images taken at ③, for three different β angles.

Table 1 lists the experimental and theoretical parameters used.

Experimental Value		Calculated Value	
w_1	979 μm	$k = \frac{2\pi}{\lambda}$	$7.90 \times 10^6 \text{ m}^{-1}$
w_2	987 μm	w	$983 \pm 4 \text{ } \mu\text{m}$
λ	795 nm	β	$\approx (0.1 \text{ to } 1.6) \text{ mrad}$

Table 1. Experimental and theoretical parameters.

We obtained two sets of results, shown in table 2. Bold face was used to differentiate between them.

Location	Power on upper arm		Power on lower arm		Total power	
	H mode[mW] ± 0.01		V mode[mW] ± 0.01		H+V mode[mW] ± 0.01	
①	/	/	/	/	6.29	8.4
②	2.61	3.86	3.14	3.84	5.75	7.7
	H mode[mW] ± 0.01		H mode[mW] ± 0.01		Transmitted mode [mW] ± 0.01	
③	1.13	1.75	1.62	1.74	4.50 (2.75)	6.80 (3.49)
	V mode[mW] ± 0.01		V mode[mW] ± 0.01		Reflected mode [mW] ± 0.01	
④	1.32	1.85	1.33	1.86	0.91 (2.65)	0.5 (3.71)

Table 2. Measurements of the power at different positions on the interferometer. One set is in plain text and the other is in bold face.

2.2.4. Discussion. The results on table 2 –plain text– fit our model (12) if we take $\epsilon \rightarrow 0$ and $\beta \approx 0.23 \pm 0.02$ mrad, which corresponds to an efficiency of 71.5%. The set of results in bold face fits the model with a $\beta \approx 0.1 \pm 0.02$ mrad, leading to an efficiency of 80.9%. Although we have a large visibility from (15): $93 \pm 3\%$, the experimental visibility from the data is 86%. The difference comes from assuming $\epsilon = 0$ and $U_{10} = U_{20}$ from (15). In the case that $\epsilon = 200\mu$, we obtain that $e^{\frac{-\epsilon^2}{2w^2}} = 97.9\%$ leading a visibility ($\beta \approx 0.1 \pm 0.02$) of $91 \pm 3\%$.

Moreover, using the measurements at point ②, the efficiency of PBC is 91.7%, but as we have seen in section 1.1 this combination can only be applied once. Therefore, if an efficient source of non-polarized light with only two inputs is needed, this is a good solution.

The values that β and ϵ can take in the Gaussian beam interference are limited by the resolution of the screws. To have a large efficiency, is to have large resolution of the screws of the mirrors.

2.3. Optical power amplifier: tapered amplifier

We use a tapered amplifier (m2k laser TA-0800-0500) to amplify ~ 20 mW of seed laser power to ~ 500 mW. The setup, consisting of alignment mirrors, in-coupling and out-coupling optics including astigmatism correction, and a Faraday isolator, is shown in figure 7.

The tapered amplifier [5] needs a special current driver, capable of delivering up to 2 A, having a slow starting, and a very precise control of the output current, leading to a precise control of the optical power.

Up to 20 W of heat from the amplifier can be dissipated to the heat sink via a thermoelectric cooler (TEC) controlled by a temperature controller.

Both the laser driver and the temperature controller require calibration, the former one to set correctly the current and to fix the current limit; the latter to set the gain of the controller in order to obtain the desired temperature change rate, or to ensure a stable temperature.

We have built a chassis for the TA, allowing mechanical stability, temperature control, electrical contacts and a housing for the aspheric lenses that must be separated 6 mm from the TA.

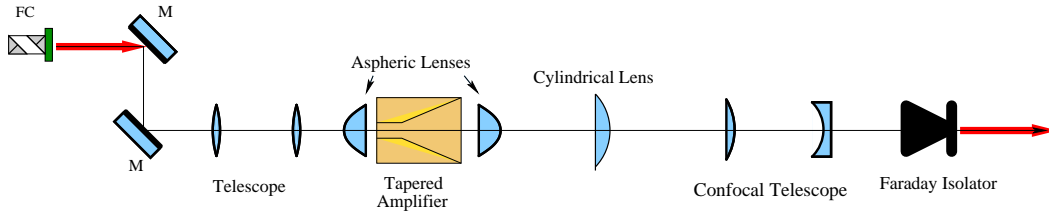


Figure 7. Setup of Optical Power Amplifier using Tapered Amplifier or Master Oscillator Power Amplifier. FC: Fiber coupling, M: dielectric mirror.

Currently, this mechanical support is being optimized, aiming to improve the optical coupling between the TA mode and the seed mode. This step is crucial to produce a large output power.

3. Conclusion

We have demonstrated the use of the *coherent beam combining technique* with an efficiency of 80.9%. Besides, in case we need a non-polarized source (PBC), we can

obtain 91.7% efficiency. The model presented in section 2.1 has the advantage that it predicts the visibility of two Gaussian beams when they interfere in a general way, and therefore gives an estimation of the CBC efficiency. We presented a new technique to lock the output power, using a split (quadrant) detector. We have run a tapered amplifier, whose chassis is being modified.

Our next goal is to combine the power of two tapered amplifiers at 795 nm. In this way, we can have a polarized output of around 800 mW.

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I would like to thank Sergio Barreiro for designing an enclosure (chassis) for the TA, and for his help with designing another one.

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